MEMS SHUTTERS FOR SPACECRAFT THERMAL CONTROL

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As they are envisioned for future missions, small spacecraft, including nano and picosats, will require low power and light weight thermal control systems due to their small power and mass budgets. Variable emittance coatings, including micro-machined shutter arrays, will be flown as demonstration technologies on NASA's New Millennium Program ST5 spacecraft. The latest prototype devices are arrays of 150 µm x 6µm micro-machined and gold-coated shutters. Electrostatic comb drives are used to actuate the shutters to expose either the gold coating or the high emittance substrate to space. The prototype arrays have been designed and fabricated at Sandia National Laboratories using their SUMMiT V process. Present prototype die are 2.5 mm x 5 mm and consist of nine independent shutter arrays. For the flight units, 38 die, each with 72 shutter arrays will be combined on a radiator and independently controlled. It is expected that this will allow linear control of the effective emittance.

The prototypes have undergone extensive thermal and lifetime testing, both in air and under vacuum. The paper will discuss the latest results including measurements of variable emittance, design aspects of the shutter arrays and the thermal control radiator, the ST-5 thermal conditions and the integration of the radiator into the spacecraft.

Introduction

The use of nano- and pico-satellites in present and future space missions requires a new approach to thermal control. The power and mass budgets limit battery availability and prohibit the use of electric heaters for active thermal control. Nevertheless, many of the missions envisioned for these types of spacecraft require flexibility in the thermal design of the spacecraft as well as short design cycles to limit costs. One possible approach is a radiator coating with a variable infrared emissivity that can be actively adjusted in response to variations in the thermal load and environmental conditions. An elegant solution for small spacecraft involves the use of micro-machined miniature shutter arrays on the radiator to control its emissivity.[1,2] Electrostatic linear motors open and close theses arrays while consuming very little electrical power, allowing the radiator to be adapted to a very broad range of thermal requirements during flight.

New Millenium Space Technology 5

The Space Technology 5 (ST5) mission is the fourth space mission in NASA's New Millennium Program. The mission will fly three miniature spacecraft, each 42 centimeters (17 inches) across, 20 centimeters (8 inches) high, and with a weight of 21.5 kilograms (47 pounds) in a Molniya orbit with 185 km perigee and 35,786 km apogee altitudes. The mission is planned for launch in 2004 as a secondary payload on an expendable launch vehicle.

The mission objective is to test methods for operating a constellation of spacecraft as a single system and to test and flight-validate seven innovative new technologies in the harsh space environment of Earth's magnetosphere. One of these technologies is variable emissivity coatings for active thermal control. MEMS variable emittance coatings (VEC) are one of technologies on ST5 to be used for thermal control. The two other technologies to be tested are an electrostatic thermal switch and electrochromic coatings. Each of these technologies will cover a 90 cm^2 radiator, with two technologies per spacecraft. One technology will be flown on the top deck and the other on the bottom. The technology objective is to validate the variable emissivity coatings as functional radiator while mitigating risk to the spacecraft due to VEC failure.

The exact orbit depends largely on the launch opportunity, and the spacecraft thermal design has to be prepared for the extreme cases. This is precisely one of the applications of the VECs, to generate a thermal design that works over a broad range of conditions, allowing for greater flexibility in the spacecraft design.

MEMS Shutter Concept

The initial concept for the MEMS VEC radiator consisted of louver arrays, each louver about 300 µm x 500 µm, with 400 of these louvers per square centimeter. The louvers were designed to fully open and expose a high emittance space, or in the closed state, expose their gold surface[1, 2]. While the feasibility of this concept has been demonstrated with prototype arrays, the harsh conditions during launch and in space required a thorough re-evaluation of the design which towards a more rugged approach.

The current flight design based on arrays of shutters is shown in Fig. 1, was a compromise between reliability and performance. Arrays of small shutters, 6 µm wide and 150 µm long, expose either a silicon substrate or a gold substrate, depending on the position of the electrostatic comb drives actuators. In order to reduce friction, the arrays, 1767µm x 876µm, are suspended on polysilicon springs 2 µm above the silicon substrate and actuated by 6 groups of electrostatic comb drives. The motors occupy about 20 percent of the shutter array area, and therefore the maximum emissivity change for each of these arrays is $0.4 \times \Delta\varepsilon$, where $\Delta\varepsilon$ is the difference between the high (silicon and below) and low emissivity (gold) substrate.

The shutter arrays were fabricated using Sandia's Ultra-Planar Multi-Level MEMS Technology 5 (SUMMiT V), a 5-level polysilicon surface machining process, that offers significantly increased system complexity[3] over other available MEMS processes. The SUMMiT V process consists of a 0.3 µm thick polysilicon electrical interconnect layer (poly0), and 4 mechanical levels polysilicon separated by a sacrificial polysilicon dioxide films (poly1 and poly2 are 1 µm and 1.5 µm thick, respectively, and separated by 0.5 µm silicon dioxide, poly 3 and 4 are 2.25 µm thick and separated by a 2 µm sacrificial layer). The sacrificial layers beneath poly3 and poly4 are planarized, which eliminates some of the processing artifacts of other surface micromachining processes due to the conformal film deposition, which propagates the topography to all successive layers.

One result of the complexity of the SUMMiT V process is a new class of high force, low voltage actuation systems. Since the force obtainable from an electrostatic comb drive is roughly proportional to its area and the thickness, the thickness increase with the 5-layer process reduces the required area for the same force.[4]

The shutter arrays are based on the use of these electrostatic comb drives. Each actuator element occupies an area of 225µm x 183µm, has a displacement of 6 µm, and produces several hundreds of microNewtons of force, suitable for moving the shutter arrays. Six groups of actuators are used to control one shutter array.

For the low emissivity, the shutter arrays, as well as the corresponding positions on the substrate, needed to be coated with gold. The SUMMiT V process does not include any metal layers, therefore the gold coating must be deposited after the shutters are released. This post processing step also coats the substrate at the same time. In order to allow the deposition process, two features were added to the design. All of the interconnects between the bond pads and the actuators were to be embedded into the substrate to prevent shorting when the gold coating is applied. Also, the bond pads were designed to be self-

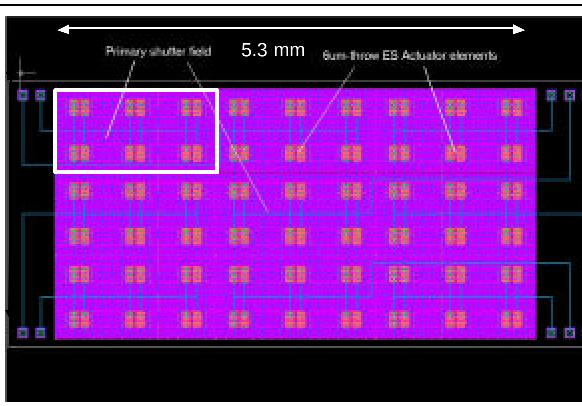

Figure 1. Prototype design for the shutter array. Each shutter element is 6 µm wide and 150 µm long.

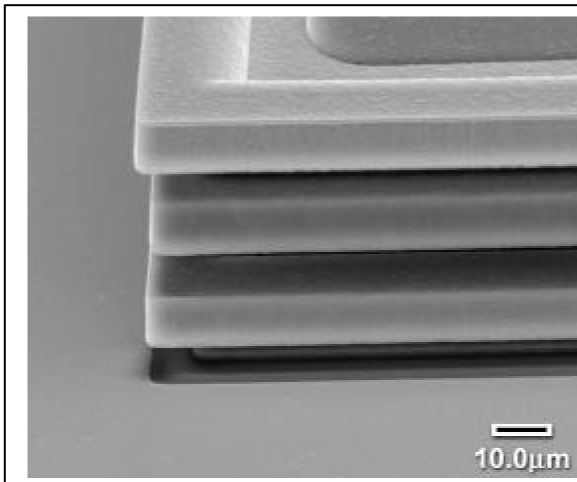

Figure 2. SEM of a bond pad after gold coating. The self-shadowing design prevents the gold from shorting to the pad.

Figure 3. SEM of the gold-coated actuator structure.

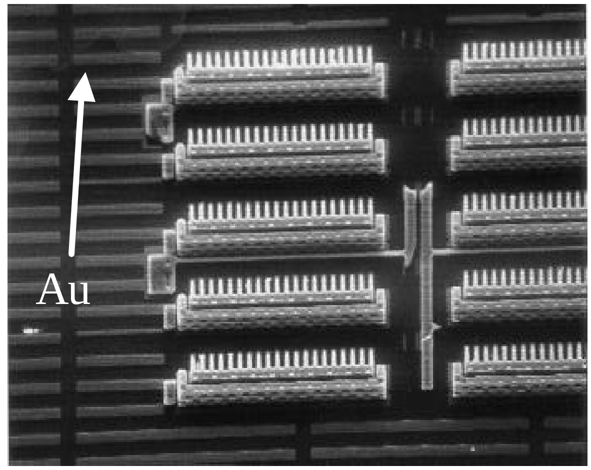

Figure 4. SEM of the array structure with the array removed. The gold shutter structure deposited onto the substrate is visible.

The shutters are spring-loaded to remain in the closed position and require a voltage of about 30-35 V to be applied to move 6 µm and expose the uncoated, high emissivity portion of the substrate. The current flow is determined by the resistor to bleed the charges off the actuator and can be held below a few µA, which will not result in high power consumption during operation. In addition, this allows for simple control algorithms to be used. The controller is designed to move each shutter at least once a second to prevent a shutter from remaining in the same position for an extended period of time, which makes it less susceptible to become stuck.

One advantages of the shutter design is its robustness and reliability, being directly coupled to the comb drive actuator without any hinge structures. The planar geometry will also prevent light absorption for low angles of incidence. This was a problem for large louvers that exposed the radiator substrate to the low angle illumination when in the open position.

A disadvantage of this design is obviously the limitation to less than 40% emissivity variation (including the actuators). For a future generation, this could be improved adding another layer of shutters, which is possible with the SUMMiT process. Another disadvantage is the large moving area, which could jam due to particulates or debris. Many experiments will be performed during the space qualification process to estimate the lifetime of the devices under space conditions.

Radiator assembly

For the ST5 radiators, an area of 90 cm^2 needs to be covered with shutter arrays. A drawing of the radiator assembly is shown in Fig. 5. The radiator is divided into two partitions, each of which will hold 18 radiator die. Each die is 12.65 mm x 13.03 mm and contains 72 of the shutter arrays. The layout of the die is shown in Fig. 6. All arrays on the same die are connected to the same voltage source at each corner of the die. Each actuator array is connected via a 20 mA MEMS fuse, which will blow in the case the array is shorted to ground, to prevent loading the voltage source. The voltage to the fuse runs on a poly-silicon bus, after the fuse it is connected to the array via embedded interconnects. Groups of six die are connected to the same controller line. Each radiator also is connected to six temperature sensors, with two directly read by the Command and Data Handling (C&DH) and the remaining four read by VEC controller. The controller provides 35 V to drive the arrays, returns temperature and status data to the C&DH, and receives the commands from the C&DH:, manual open, manual close, and automatic operation. In automatic mode, the radiator will go through an experimental sequence to determine a low and a high emissivity temperature and then maintain the radiator at a set temperature in between the extremes. It also will determine the capacity of the radiator assembly, which is a measure of the number of working arrays, and return this value in the status data to the C&DH.

Thermal Aspects

The figure of merit for this experiment is the temperature difference between high emissivity state and low emissivity state of the radiator for the cold (230 K) and the hot (330 K) case. The radiator consists of about 47 g Al and 7 g Si, which adds to a heat capacity of 50 J/K. The temperature differences (after 20 min to

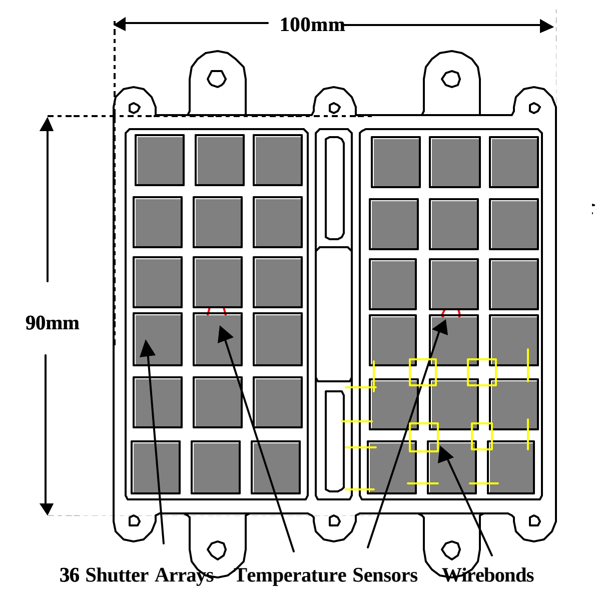

Figure 5. Drawing of the radiator assembly.

stabilize) are shown for the cold case and the hot case for different emissivities in Fig. 7 as a function of the conductance to the spacecraft. At present, this conductance is assumed to be 0.1 W/K. For a realistc emittance of 0.2 – 0.4, the temperature differences are in the order of 4 to 10 K at this conductance, and even higher if the conductance is decreased. The resolution of the thermal sensors is in the order of 50 mK, which would be sufficient for these temperature differences. It also can be shown, that from the knowledge of the number of working shutters (independent of what position in which the nonworking ones are stuck) and the temperature measurements, the variation in the emittance, and therefore any end-of lifetime effects, can be determined.

One of the difficulties for this experiment is to increase the active emittance change. Already limited to an active are of 40% by design, any non-active surface such as the space between die, the radiator housing, or the connectors, will reduce this area even further. In addition, the emissivity of the substrate, silicon on epoxy, is less than 1. Since Si is transparent over most of the IR range, the emissivity of the epoxy needs to be increased. Infrared images taken at 8-12 µm of the gold-coated shutter layout as depositied on a on a silicon test wafer are shown in Fig. 8. The wafer was mounted on an anodized aluminum radiator. The emittance differential between the open and the closed shutters is limited to 0.3, due to the low emissivity of the silicon. Additional points of concern for the total emittance variation come from a cover protecting the structures from any small debris. While the exact polymer material has not been determined, any IR

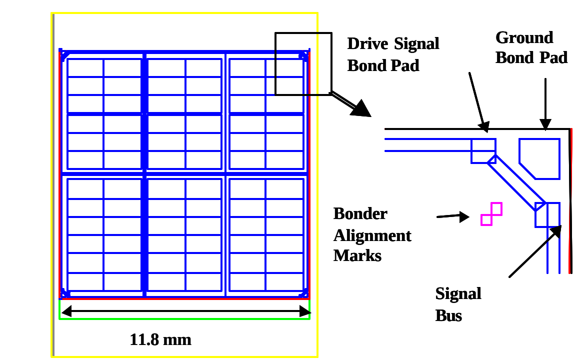

Figure 6. Layout of the MEMS VEC array die. The die is 12.65 x 13.03 mm in size and contains 72 shutter arrays.

absorption above 5 µm in the cover will further reduce the emittance variation.

MEMS Reliability in Space

The ST5 MEMS VEC experiment will be a unique chance to retire some yield and reliability issues through flight validation. The radiator area requires, for the three flight hardware radiators, a total of 108 fully working dies, out of a total of the order of 800-900 die fabricated. This will provide an exhaustive database on the yield of such a large area MEMS design, the postprocessing, coating, and packaging. In addition, the experiment will help to increase the limited knowledge about the reliability of moving MEMS structures subjected to launch and the harsh space environment. Even if the materials aspects cannot be solved to increase the emittance variation of the MEMS VEC radiator, to understand how well it works and in which conditions will be critical in the development of a next prototype for a MEMS shutter, or any moving MEMS devices. In addition, the effects of pre-launch storage must also be taken into consideration. A non-exhaustive list of reliability issues besides the effects of pre-launch storage and launch include wear, fatigue, contamination, and radiation effects.[5]

Although stiction has not been observed in the prototype devices, the MEMS louvers are probably susceptible to this failure mechanism as a result of electrostatic interactions, capillary forces, or even localized cold welding.[6] These concerns are addressed in several ways. For example, proper ground design minimizes the potential mechanical seizure due to electrostatic clamping. The only devices not grounded are the stationary fingers on the comb drive actuators, which connect to the high voltage supply. The ground design and gold coating also prevents

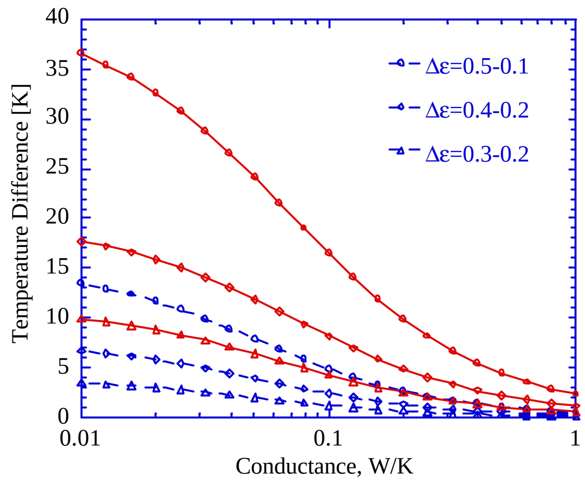

Figure 7. Temperature difference between high-and low emissivity case for different emissivities as a function of the (parasitic) conduction. Solid: Hot Case (330 K), Dashed: Cold Case (230 K), Specific Heat 50J/K.

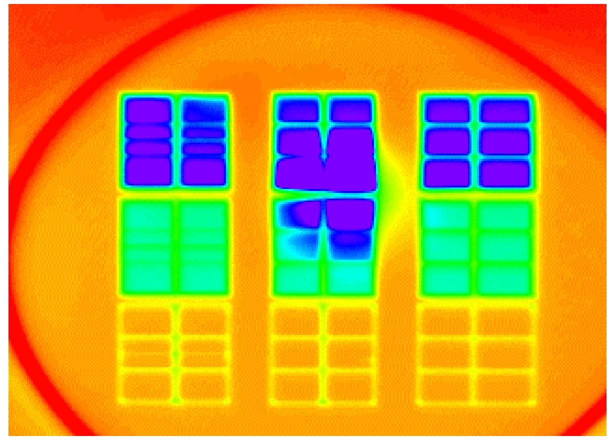

Figure 8: IR image, 8-12 ? m, of a Si wafer coated with 30 nm Cr and 30nm Au in a pattern corresponding to a closed (ε=0), open (ε=0.30) , and no shutter (bare Si, ε=0.6).

charge built-up due to high-energy radiation, as it is expected for the orbit of ST5.

Excessive condensation of moisture during pre-launch storage will be mitigated through the use of an removable cover which seals the radiator in dry air, and at the same time prevents debris and contact with the MEMS devices.

Relative humidity (RH) levels in excess of 70% have been associated with degraded mechanical performance attributed due to increased stiction. However, elevated frictional wear between contacting parts has been observed in extremely low RH environments.[7] Due to the negligible RH of the intended operational environment, the possible degradation of the guides for the shutters over the device lifetime is an important issue. Minimum lifetimes will be on the order of 10,000 to 50,000 cycles depending on the control algorithms and the thermal conditions. The design of the shutter arrays limits friction to a minimum. There are no rubbing parts, the moving parts are elevated, held in place by spring supports. Lifetime in vacuum for the prototype devices has been determine to be more than 3 months at a 4 Hz actuation frequency.

As additional risk mitigation during operation, all shutters are connected via a 20 mA fuse. We have seen that in most cases a short accompanies damage to the shutters to ground. In this case, the fuse will blow and the shutter array is decoupled from the high voltage drive and will not continue to load the voltage converter.

The results of the tests on the flight devices will also help to generate new requirements and standards for test matrices on MEMS devices.

Conclusions

It has been shown in multiple models[3] that VEC technology offers significant advantages over current approaches for radiators in low UV environments. The heater power, mass, and cost savings that can be realized with these systems are potentially significant for many future spacecraft design applications. In addition, VEC coatings allow for a more flexible thermal design, which is important for spacecraft such as ST5 that are launched as a secondary payload and the orbit parameters are not well defined during the design period. The ST5 mission will demonstrate three VEC technologies and, if successful, provide validation for their use on future spacecraft. At this point, fully actuated prototypes of MEMS shutter arrays have been fabricated and will undergo critical reliability and space qualification testing before the fabrication of the 90 cm^2 radiator for ST5 will begins. Finally, the inclusion of the MEMS VEC technology on ST5 will provide important information about the performance and the reliability of actuated MEMS devices in space.

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